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**LASER PULSE HEATING SIMULATION OF FIRING
DAMAGE ON COATED GUN BORE SURFACES**

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13. ABSTRACT (Maximum 200 words) Laser pulse heating was used to simulate thermal effects on plated gun bore surfaces during firing. The aim is to provide new insights into the erosion process and develop the method as an evaluation tool for developmental coatings. This report discusses results of cyclic thermal pulsing experiments on high contractile and low contractile chromium plated gun steel, sputtered tantalum coated gun steel, and uncoated steel.				
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TABLE OF CONTENTS

	<u>Page</u>
ACKNOWLEDGEMENTS	iii
INTRODUCTION.....	1
Thermal Shock Effects in Chromium.....	1
Thermal Shock Effects on Sputtered Tantalum Coatings	2
Thermal Shock Effects on Uncoated Gun Steel.....	2
EXPERIMENTAL METHODS	2
Laser Pulse Heating Apparatus	2
Specimens and Analysis.....	4
RESULTS AND DISCUSSION	4
HC and LC Chromium	4
Sputtered Alpha and Beta Tantalum	7
Uncoated Steel.....	8
SUMMARY	9
REFERENCES	10

LIST OF ILLUSTRATIONS

1.	Schematic of pulsed laser heating apparatus.....	2
2.	Uncoated steel specimen exposed to laser pulse heating showing effects of 1, 2, 5, and 20 pulses	3
3.	Typical plot of thermocouple voltage versus time after laser pulse heating for a thermocouple adhered to the rear surface of the specimen	3
4.	Laser pulse heated specimen showing metallurgical changes, chromium cracking, and damage initiation in steel after 20 pulses.....	4
5.	Damage initiation and propagation in steel in a 120-mm gun bore	5
6.	Five pulses.....	5
7.	Twenty pulses.....	6
8.	Twenty pulses (unetched version).....	6

9.	Twenty pulses (etched version).....	6
10.	Section of uncoated steel specimen after 20 laser pulses showing thick reaction layer and heat-affected zone.....	8

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INTRODUCTION

Laser pulse heating was used to simulate thermal shock loading on gun bore surfaces during firing in an attempt to gain new insights into the erosion process. Although details of the erosion process on gun bore surfaces are poorly understood, the major contributors to erosion damage are known to include thermal effects, chemical attack by propellant gases, mechanical wear from projectile passage, and mechanical loading from gas pressurization. Gun bore surfaces are typically subjected to short (5 to 10 milliseconds) pulses of high thermal energy during firing of a round. Included among the deleterious thermal effects are melting, metallurgical transformations, thermal and transformational stresses, and surface cracking.

Bore surfaces are often electroplated with high contractile (HC) chromium to enhance resistance to erosion. (The terms high contractile and low contractile (LC) refer to the differences in shrinkage and cracking during deposition and annealing of HC and LC chromium electrodeposits). Low contractile chromium electroplated coatings for large caliber gun bores were recently developed in order to exploit benefits of coatings with lower crack densities. Current efforts are also underway in developing alternatives to chromium (e.g., magnetron-sputtered tantalum).

Besides providing new information on issues related to erosion, laser pulse heating may also serve as a means for evaluating prospective coatings. For example, as with electrodeposited chromium, candidate bore coatings are generally prepared under nonequilibrium conditions, so their microstructures are metastable, and one cannot generally predict the effects of firing on such coatings. Laser pulse heating can conveniently provide this kind of information (e.g., evolution of metallurgical changes and cracking with number of pulses and pulse energy).

Thermal Shock Effects in Chromium

There is extensive experience with gun bore protective coatings including HC and LC chromium (refs 1-3). The most extensive compilation of this experience remains the 1946 National Defense Research Committee Report entitled, "Hypervelocity Guns and the Control of Gun Erosion" (ref 2).

A recent survey study of chemical attack initiation in HC and LC chromium plated gun bore surfaces (refs 4,5) showed that damage to the steel substrate begins at the tips of chromium cracks by propellant gas/metal reactions. The reaction products appear as gray layers or gray zones in the steel. These layers are iron oxide, iron sulfide, or mixtures of these two compounds. Wherever there is a heat-affected zone, the white layer forms in the steel adjacent to the gray layer, indicating that carburization occurs along with the oxidation processes.

High contraction chromium is significantly more cracked than LC chromium after firing (refs 3-5). The difference between HC and LC contraction during the deposition and the subsequent 200°C anneal to drive out co-deposited hydrogen is responsible for the difference in crack density prior to firing. The as-plated LC chromium is uncracked, while the as-plated HC already possesses a high density of embedded and surface cracks. One of the unresolved questions is whether the time at high temperature during firing is sufficient to permit chromium contraction to remain a factor in the increase in chromium cracking during firing. Another question is whether the thermal shock process alone can damage the steel substrate. Laser pulse heating is currently being used to address such issues.

Thermal Shock Effects on Sputtered Tantalum Coatings

Sputtered tantalum coatings are under consideration for gun bores. Sputtered tantalum frequently deposits as a mix of alpha phase and a hard, brittle, metastable beta phase. Laser pulse heating was applied to sputtered alpha and beta phases to provide comparisons of the relative thermal shock resistance of the two phases.

Thermal Shock Effects on Uncoated Gun Steel

Laser pulse heating was applied to uncoated steel specimens to determine the effects of cyclic thermal pulsing on steel and to simulate the effects of repeated firing on unplated bores and in gun bore areas where the chromium coating had been removed by spallation

EXPERIMENTAL METHODS

Laser Pulse Heating Apparatus

Radiation of wavelength 1064 nanometers from a neodymium-doped yttrium aluminum garnet (Nd:YAG) laser is delivered to the test specimen surface as shown in Figure 1. Lenses focus the light from the laser rod into a 10-meter, coiled length of all-silica optical fiber with core diameter of 600 micrometers, cladding diameter of 720 micrometers, and numerical aperture of 0.20. An optical fiber is used both for convenience and for assurance of a uniform energy distribution at the sample surface. A lens assembly is used at the output of the fiber to form a magnified image of the end face of the optical fiber onto the specimen surface. Thus, the spatial distribution of energy at the specimen surface is approximately uniform over a circular spot with a diameter that depends upon the diameter of the optical fiber core and the magnification of the output optics.

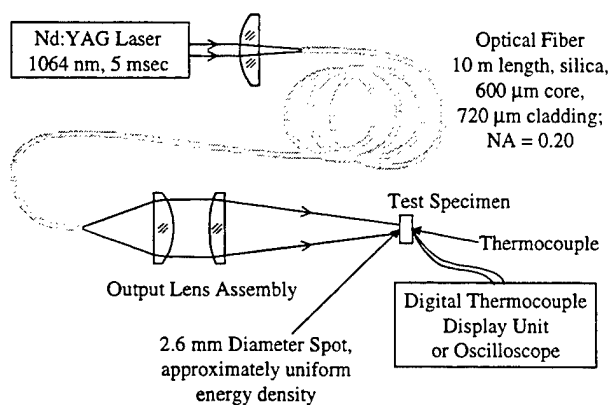


Figure 1. Schematic of pulsed laser heating apparatus.

The pulse duration is 5 milliseconds (Full-Width Half-Maximum (FWHM)), and the spot diameter at the specimen surface is typically 2.6 millimeters. Given typical coating thicknesses of 0.1-mm, the spot diameter to coating thickness ratio is 26, so that a large portion of the central spot area can be assumed to replicate the essentially one-dimensional heat flow through the coating at the bore surface.

Figure 2 shows a 6-mm x 6-mm uncoated steel specimen that was subjected to a series of pulses. The top left area was exposed to one pulse, the bottom left two pulses, the top right five pulses, and the bottom right area twenty pulses.

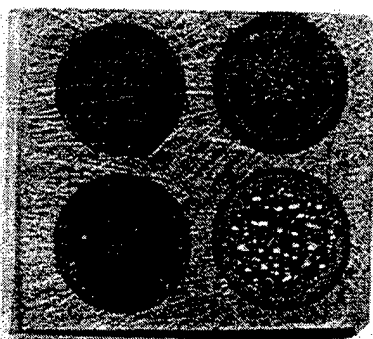


Figure 2. Uncoated steel specimen exposed to laser pulse heating showing effects of 1, 2, 5, and 20 pulses.

The figure illustrates one of the conveniences of the method, in that numerous experiments can be performed on a single, small specimen.

For most coatings, a significant portion of the laser energy is reflected rather than absorbed. In the present study, the absorbed energy was measured calorimetrically. Typically, the test specimen is about three millimeters thick and cut to a square six millimeters on edge.

A thermocouple is adhered to the back surface and the specimen is thermally insulated. Figure 3 shows a typical plot of the thermocouple voltage after laser pulse heating for a thermocouple adhered to the back surface of the specimen. This method was used to maintain the absorbed energy per pulse at approximately 1 J/mm^2 , which is expected to be representative of conventional high-temperature propellants.

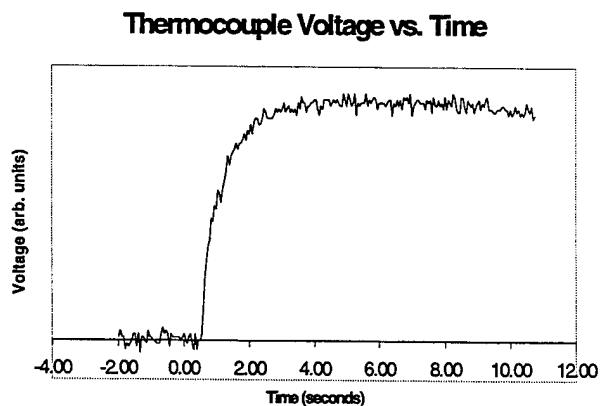


Figure 3: Typical plot of thermocouple voltage versus time after laser pulse heating for a thermocouple adhered to the rear surface of the specimen.

Specimens and Analysis

The substrates for chromium electrodeposition and planar sputtered tantalum are 1 x 5 x 0.1-inch ASTM A723 (gun steel) steel plates in the quenched and tempered state (nominal 160 Ksi yield strength). The electrodeposited specimens were generally given a 200°C anneal to drive out co-deposited hydrogen.

Analyses methods included scanning electron microscopy (SEM), dilatometry, electron microprobe analysis, energy dispersive spectroscopy, wavelength dispersive analysis, and atomic force microscopy.

RESULTS AND DISCUSSION

HC and LC Chromium

Figure 4 is an optical micrograph of a cross section of an HC chromium electrodeposit on a steel substrate.

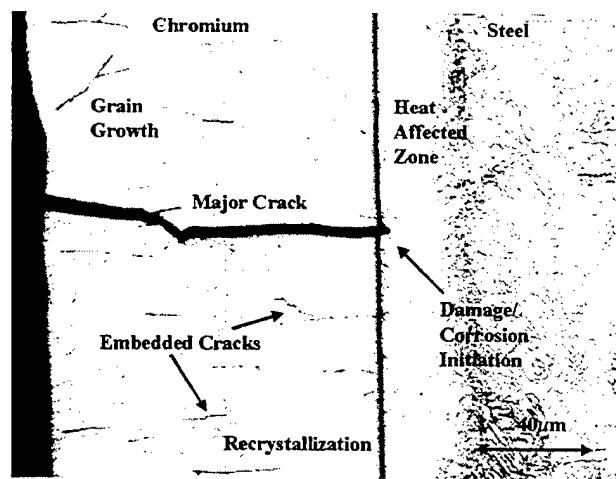


Figure 4. Laser pulse heated specimen showing metallurgical changes, chromium cracking, and damage initiation in steel after 20 pulses.

This specimen area was subjected to 20 pulses at incident energy 2-3 J/mm². The figure exhibits all the features of a fired chromium plated gun bore section as shown in Figure 5. This includes recrystallization and grain growth of the chromium, wide cracks in the chromium, a heat-affected zone in the steel, and corrosion attack (iron oxide) at the tip of the cracks in the chromium. The fine surface and embedded cracks are present in the as-prepared condition.

Figure 5 is from a 120-mm gun tube that had fired approximately 80 experimental rounds and 225 conventional rounds (See References 4 and 5). The figure shows sites of damage initiation with associated gray layers and white layers. Also shown is an area where damage in the steel has progressed beyond damage initiation to crack initiation. The major cracks (cracks that extend through the coating) in Figure 4 are the result of thermal pulsing alone. This illustrates that mechanical loading during firing is not a major factor in the enlargement of chromium cracks. Experiments were also conducted to compare the development of cracks on HC and LC chromium specimens after 1, 5, and 20 laser pulses.

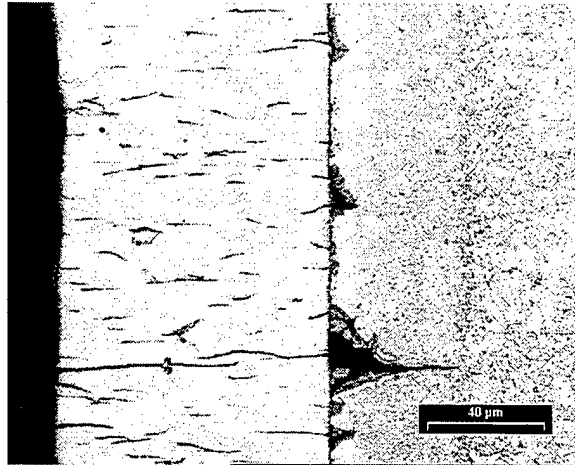


Figure 5.. Damage initiation and propagation in steel in a 120-mm gun bore.

The calorimetric method was used to maintain an approximately constant absorbed energy of 1 J/mm^2 . The thermal shock cracking in the laser-heated area develops by enlargement of the preexisting surface cracks that were generated in the specimen during the deposition and the subsequent anneal to remove hydrogen.

By contrast, the cracks in LC chromium, where there are no preexisting cracks, develop by initiation and growth. The resulting major crack widths after 20 pulses are comparable in the in LC and HC cases, but the crack densities are substantially lower, in good agreement with data for fired gun tubes (refs 4,5). Also, the high density of preexisting, embedded cracks in HC chromium are not present in the LC case. Dilatometer studies show much smaller length contraction ($\sim 0.3\%$ versus 1%) in LC relative to HC chromium on annealing (unpublished results). This is in rough accord with the observed difference in major crack density, indicating that the contraction process plays a role.

Figures 6 through 9 are a series of SEM micrographs of various damage initiation sites at the chromium/steel interface for the specimen shown in Figure 1. Figure 6 is a typical result for 5 pulses. Figures 7, 8, and 9 are typical results for 20 pulses.

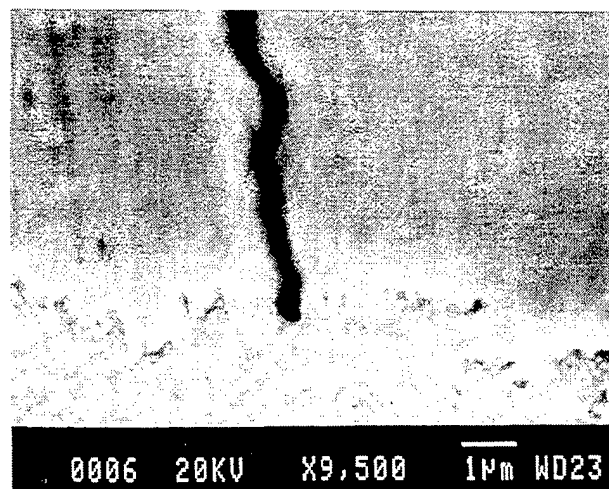


Figure 6. Five pulses.



Figure 7. Twenty pulses.

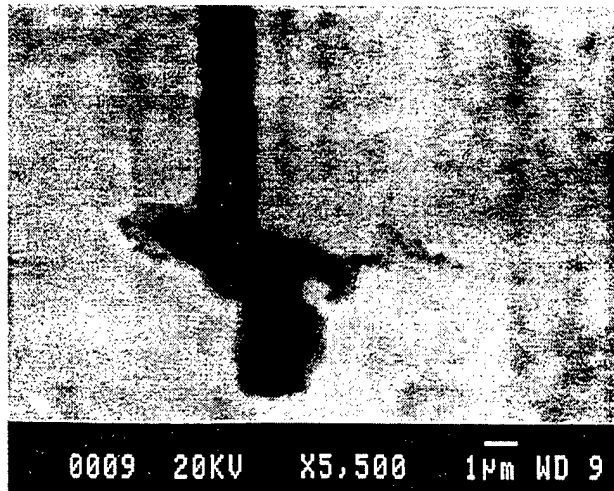


Figure 8. Twenty pulses (unetched version).

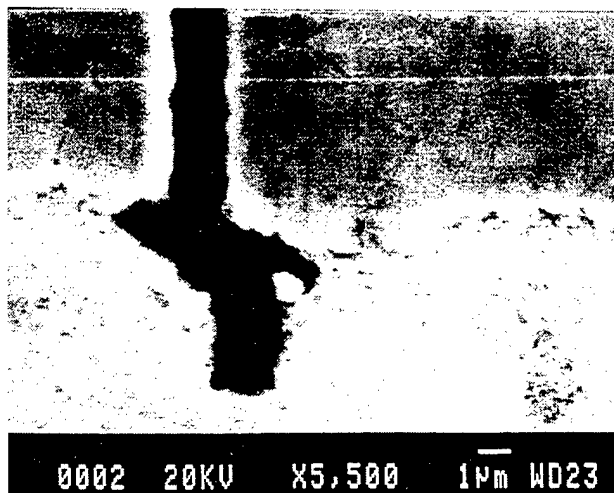


Figure 9. Twenty pulses (etched version).

The major cracks extend all the way through the chromium coating to the substrate. As shown in these figures, the damage extends into the substrate to form blunt corroded extensions of the chromium fractures in the steel heat-affected zone (untempered martensite). Figures 8 and 9 are unetched and etched versions to show the reaction zones (gray layers) surrounding the crack extension into the steel. Wavelength dispersive analysis identified these reaction zones as iron oxide (wustite, FeO). Small fissures are present in the iron oxide and their orientations are generally perpendicular to the steel surface of the pit. These features are similar to those seen in the reaction zones of fired tubes (refs 4,5).

The reaction layers here are relatively thin so that chemical attack (rapid oxidation) plays only a limited role in the development of the damaged area. One difference between these results and the damage initiation sites in fired guns, as shown in Figure 5, is that the pitted areas in fired guns are often more solidly filled with oxide and/or sulfide (refs 4,5). This can be attributed to differences in number of rounds and oxygen partial pressures during firing.

Sharp cracks into uncorroded steel are not observed in the laser pulsed specimens in the present study. Similarly, damage initiation in gun tubes rarely involves sharp cracks (refs 4,5).

Dramatic blunting of the chromium cracks by the steel evidently gets a large contribution from ductile fracture since the oxidation appears to be confined to the damage surface. How this can occur in the brittle, untempered martensite zone may be explained by considering the following details. The large thermal stresses generated during laser pulsing assure that substantial cyclic plastic flow will occur, especially in the weak austenite. (Typical yield strengths of austenitic stainless steels above 300°C are 20 Ksi or less.) Because of the constraint of the adjacent unheated material, the high thermal stresses will cause compressive yielding during the heating phase, particularly upon austenitization. A corresponding tensile yielding will occur in this austenite during the subsequent quench phase. The tensile loading will be interrupted by the volume expansion of the martensite transformation at $\sim 280^{\circ}\text{C}$. The large volume expansion during martensite formation produces the compressively stressed, heat-affected zone (ref 6). The heat-affected zone is thus a brittle, high-strength untempered martensite (typically 240 Ksi). Blunting by plastic deformation cannot occur in this layer. Therefore, the blunting of chromium cracks and any ductile fracture propagation must have occurred in the soft austenite prior to martensite formation.

Sputtered Alpha and Beta Tantalum

Preliminary laser pulse tests were performed on a nominally 4-mil (100-micron) coating of sputtered alpha and beta phases. The coating was deposited onto a 0.1-inch thick steel substrate using planar magnetron sputtering at a sputtering pressure of 10 millitorr. The phases co-exist on the same specimen with the beta formation occurring in the central region and the alpha phase deposited beyond. The beta phase coating cracked as a result of the thermal shock from the laser pulse. No cracking was observed in the alpha phase, indicating good resistance to thermal shock. Studies are continuing to establish the effects of cyclic thermal pulsing on phase transformations in the metastable beta phase.

Uncoated Steel

As shown in Figure 2, an uncoated specimen of gun steel was subjected to a series of pulse treatments with absorbed energy maintained at approximately 1 J/mm^2 . A heat-affected zone forms after a single pulse. The depth of the heat-affected zone does not appear to be a function of the number of pulses, but the microstructure can be observed to progress smoothly from the initial tempered martensite to the hard, etch resistant, untempered martensite layer. Thus, the depth of the heat-affected zone may serve as an approximate measure of the temperature at that point using the equilibrium phase diagram. This is possible because after a few pulses, the carbon can be assumed to have gone into solution and the rapid heating, estimated as high as $\sim 10^6 \text{ }^\circ\text{C/s}$, is actually an "upquench," bypassing the diffusion-controlled, tempering process. The high-strength, untempered martensite can thus be assumed to transform directly to austenite. It follows that this unusual process also occurs on gun bore surfaces whenever a heat-affected zone has formed.

Figure 10 is a cross section through the 20-pulse zone of this specimen showing the heat-affected zone and a reaction layer at the surface. The remarkably thick reaction layer (gray layer) results from rapid oxidation at the unprotected surface. A thin layer is also observed after five pulses. It is necessarily the same as the reaction product that forms at the chromium crack tips (e.g., Figures 8 and 9) in plated specimens. An inspection of the surface shown in Figure 2 at higher magnification reveals that the oxide layer has melted during laser pulsing. This is consistent with the low eutectic temperature of FeO (1371°C). Melting of the insulating FeO may be promoted by the poor thermal conductivity of the layer.



Figure 10. Section of uncoated steel specimen after 20 laser pulses showing thick reaction layer and heat-affected zone.

Melting is not observed in this steel specimen. This result, along with the general observation of rapid oxidation (refs 4,5) in fired guns, illustrates that rapid oxidation, along with the melt-wipe process, is a viable mechanism in high-rate erosion in gun bores. (Steel melting at the surface can be induced with higher-incident laser energies. This would correspond to the extreme case for erosion rates.) The results on unplated steel further demonstrate that laser pulsing in air reproduces the principal gas/metal reaction (rapid oxidation) in the fired gun tubes.

In contrast to the plated specimens, no pitting or formation of other crack initiation sites in the steel occurs after 20 pulses in the unplated specimens. Thus, the cost for general chromium plating protection is an acceleration of localized damage at the chromium crack tips.

As a test of the stress state in the heat-affected zone, hydrogen charging in an aqueous bath was applied to a laser pulsed specimen with a heat-affected zone. No cracks formed. This is consistent with the formation of compressive stresses in surface transformation hardening processes such as laser pulsing (ref 6). The presence of compressive stresses may also explain the general absence of sharp cracks at damage initiation sites in the brittle heat-affected zones in gun bores.

For completeness, it should be pointed out that in these investigations, only damage initiation sites in fired gun tubes (e.g., Figure 5) were examined because of the focus on initiation processes. The specimens often exhibit cracks that have progressed deep into the steel, well beyond the compressively stressed, heat-affected zone. In fired gun tubes, with much higher numbers of rounds than in the present laser pulse experiments, it is likely that mechanical fatigue and thermal fatigue play a role in development of deep cracks. The possibility also exists that environmental effects, such as hydrogen embrittlement (ref 7) are present in such cases.

SUMMARY

Laser pulse heating is shown to reproduce the main features of the damage process experienced at the bore surface of fired guns. The present results offer new insights into a variety of issues relating to bore coating degradation as a result of severe thermal cycling. They also illustrate the broad range of problem areas relating to bore protective coatings that can be explored with laser pulse heating.

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